Groundwater as an energy resource in Finland

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ACADEMIC DISSERTATION
To be presented, with the permission of the Faculty of Science of the University of Helsinki, for public examination in lecture room E204, Kumpula Campus, Physicum, on 18 December 2015, at 12 noon.

DEPARTMENT OF GEOSCIENCES AND GEOGRAPHY A36 / HELSINKI 2015

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Back cover photo: Marja Arola

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ISSN-L 1798-7911
ISSN 1798-7911 (print)
ISBN 978-951-51-1343-6 (pbk.)
ISBN 978-951-51-1344-3 (PDF)
http://ethesis.helsinki.fi

Layout: Pia Sonck-Koota

Unigrafia, Helsinki 2015

TO MARJA AND JULIUS

Life is too short for bullshit
- Michael Monroe

Arola T., 2015. *Groundwater as an energy resource in Finland*. Unigrafia. Helsinki. 34 pages and 7 figures.

Abstract

Increase of greenhouse gas concentrations in the atmosphere, the limits of conventional energy reservoirs and the instability risks related to energy transport have forced nations to promote the utilisation of renewable energy reservoirs. Groundwater can be seen as an option for renewable energy utilisation and not only a source of individual or municipal drinking water. Finland has multiple groundwater reservoirs that are easily exploitable, but groundwater energy is not commonly used for renewable energy production.

The purpose of this thesis study was to explore the groundwater energy potential in Finland, a region with low temperature groundwater. Cases at three different scales were investigated to provide a reliable assessment of the groundwater energy potential in Finland. Firstly, the national groundwater energy potential was mapped for aquifers classified for water supply purposes that are under urban or industrial land use. Secondly, the urbanisation effect on the peak heating and peak cooling power of groundwater was investigated for three Finnish cities, and finally, the long-term groundwater energy potential was modelled for 20 detached houses, 3 apartment buildings and a shopping centre. The thesis connects scientific information on hydro- and thermogeology with the energy efficiency of buildings to produce accurate information concerning groundwater energy utilisation.

Hydrological and thermogeological data were used together with accurate data on the energy demands of buildings. The heating and cooling power of groundwater was estimated based on the groundwater flux, temperature and heat capacity and the efficiency of the heat transfer system. The power producible from groundwater was compared with the heating and cooling demands of buildings to calculate the concrete groundwater energy potential.

Approximately 20% to 40% of annually constructed residential buildings could be heated utilising groundwater from classified aquifers that already are under urban land use in Finland. These aquifers contain approximately 40 to 45 MW of heating power. In total, 55 to 60 MW of heat load could be utilised with heat pumps. Urbanisation increases the heating energy potential of groundwater. This is due anthropogenic heat flux to the subsurface, which increases the groundwater temperatures in urbanised areas. The average groundwater temperature was 3 to 4 °C higher in city centres than in rural areas. Approximately 50% to 60% more peak heating power could be utilised from urbanised compared with rural areas. Groundwater maintained its long term heating and cooling potential during 50 years of modelled operation in an area where the natural groundwater temperature is 4.9 °C. Long-term energy utilisation created a cold groundwater plume downstream, in which the temperature decreased by 1 to 2.5 °C within a distance of 300 m from the site. Our results demonstrate that groundwater can be effectively utilised down to a temperature of 4 °C.

Groundwater can form a significant local renewable energy resource in Finland. It is important to recognise and utilise all renewable energy reservoirs to achieve the internationally binding climatological targets of the country.

Groundwater energy utilisation should be noted as one easily exploitable option to increase the use of renewable energy resources in a region where the natural groundwater temperature is low. The methods presented in this thesis can be applied when mapping and designing groundwater energy systems in nationwide- to property-scale projects. Accurate information on hydro- and thermogeology together with the energy demands of buildings is essential for successful system operation.

Tiivistelmä (in Finnish)

Ilmastolliset muutokset, perinteisten energiavarastojen rajallisuus ja energiapoliittiset tekijät ovat pakottaneet valtiot lisäämään uusiutuvien energialähteiden käyttöä. Pohjaveden hyödyntäminen on Suomessa lähes kokonaan liitetty juomavesikäyttöön ja siten pohjavettä ei yleisesti käytetä tai tunnisteta energialähteenä. Tämä tutkimus antaa pohjavesigeologiseen, termogeologiseen ja rakennusten energiankulutustietoihin perustuvaa tietoa pohjavesienergian hyödyntämisestä.

Työn tarkoituksena oli kartoittaa ja tutkia pohjaveden energiakäytön mahdollisuutta Suomessa, jossa pohjaveden luonnontilainen lämpötila vaihtelee noin 3 ja 7 °C välillä. Tutkimus tehtiin kolmessa osassa; ensin kartoitettiin koko maan kattava asuin- ja/tai teollisuuskäytössä olevien luokiteltujen pohjavesialueiden lämmitysenergiapotentiaali. Sen jälkeen tutkittiin miten kaupungistuminen on vaikuttanut pohjaveden lämpötilaan ja siten pohjaveden lämmitys- ja jäähdytysenergiapotentiaaliin Turun, Lohjan ja Lahden alueilla. Viimeisessä osiossa tutkittiin pohjaveden pitkäaikaista energiapotentiaalia 20 kerrostalon, 3 rivitalon ja kauppakeskuksen energiatarpeisiin alueella, jossa pohjaveden luonnontilainen lämpötila on 4.9 °C.

Pohjavedestä laskettua lämmitys- ja jäähdytystehoa ja – energiaa verrattiin erityyppisten rakennusten teho- ja energiatarpeisiin. Vertauksen tuloksena voitiin määrittää konkreettinen pohjaveden energiapotentiaali.

Asuin- ja teollisuuskäyttöön kaavoitetuilta pohjavesialueilta voitaisiin pohjavedestä tuottaa lämpöpumpulla noin 55 – 60 MW lämmitystehoa. Tällä teholla voitaisiin lämmittää noin 20 – 40 % Suomessa vuosittain rakennettavista asuinrakennuksista. Pohjaveden keskimääräisen lämpötilan todettiin olevan kaupunkien keskustojen alueella 3 – 4 °C korkeampi kuin luonnontilaisilla alueilla. Tämä lämpiäminen nostaa pohjavedestä hyödynnettävää lämmitystehoa noin 50 – 60 %. Pohjavesi säilytti lämmitys- ja jäähdytyspotentiaalin 50 vuoden mallinnuksessa omakoti- ja rivitalojen sekä kauppakeskuksen energiatarpeisiin nähden. Pitkän ajan pohjaveden energianhyödyntäminen alensi sen luonnontilaista lämpötilaa 1 – 2.5 °C 300 m etäisyydellä kohteesta. Tutkimus osoitti, että pohjavettä voidaan tehokkaasti hyödyntää Suomen olosuhteissa minimissään 4 °C lämpötilaan asti.

Pohjavesi voi muodostaa merkittävän paikallisen uusiutuvan energialähteen Suomessa. Kaikkien uusiutuvien energialähteiden käyttömahdollisuudet on huomioitava, jotta Suomi saavuttaa sille asetetut ilmastolliset tavoitteet. Pohjavesienergian onnistunut hyödyntäminen edellyttää laaja-alaista pohjavesi- ja termogeologista sekä rakennusten energiatekniikan osaamista ja näiden alojen yhteistyötä.

Acknowledgements

I have always been surrounded by multitalented and enjoyable people in my scientific and working life. These people have helped me to overcome difficulties in science, work or life. Many thanks to all my friends who have helped me during the work of the thesis.

I want to thank Veli-Pekka Salonen and Kirsti Korkka-Niemi for their support during my life in science. I have been privileged to benefit from your tuition from the day I started in university to the day of writing this paragraph. The University has changed over the years, but your enthusiasm in guiding geologists has not. I genuinely thank the official pre-examiners, Taina Nysten and Peter Bayer, for their review and constructive comments on the thesis.

My working family, the people in the Turku office of Golder Associates Oy, deserves huge thanks. It has always been a pleasure to work with you. I enjoy our daily life and our activities outside work. The "geological spirit" of Turku University binds us together. We have managed to create deep friendships through these years. You are fantastic!

Thanks to my financial and material supporters, Golder Associates Oy, Maa- ja Vesitekniikan tuki ry, the K.H. Rehlund foundation, the Finnish Graduate School of Geology and the University of Helsinki. You made the life of my family much easier.

Thank you Juha Jokisalo for guiding me to the world of building energy consumption. You were very patient and always had time for my questions regarding heating or cooling power. Martin Preene and Jukka Takala deserve acknowledgement, as they helped and taught me the basics of geothermal energy when we started the geothermal business at Golder. Thanks also belong to the co-writers of the articles. You carried out great work and taught me a lot. Thank you Roy Siddall for language revisions and a fantastic course on academic writing.

Thank you Mom, Dad, my late grandfather, my brothers and Jokke (my running coach), who showed a young boy how important is to persistently work hard to achieve your goals. Sepänjoki was a safe and great place to grow up…and run. The Finnish countryside, among other good things, teaches a realistic attitude towards environmental protection. This attitude is the driving force behind my work and science.

Finally, this thesis would never have been completed without the unconditional love and care of the two most important people in my life. You never complained, always supported. Even those numerous days and nights when I was a "million miles away" thinking of thermogeology instead of giving my attention to you. You are much more than I deserve. Thank you Marja and Julius!

Contents

List of original publications

This thesis is based on the following publications:

I **Arola, T**., Eskola, L., Hellen, J., Korkka-Niemi, K. 2014. Mapping the low entalphy geothermal potential of shallow Quaternary aquifers in Finland. *Geothermal Energy* 2:9. doi:10.1186/s40517-014-0009-x.

II **Arola, T**., Korkka-Niemi, K. 2014. The effect of urban heat islands on geothermal potential: examples from Quaternary aquifers in Finland. *Hydrogeology Journal* 22, 1953-1967. doi: 10.1007/s10040-014-1174-5.

III **Arola, T**., Okkonen, J., Jokisalo, J. Groundwater utilisation for energy production in the Nordic environment: an energy simulation and hydrogeological modelling approach. Submitted to *International Journal of Energy Research*.

The publications are referred to in the text by their Roman numerals. Publications I and II are published here with permission from Springer.

Author's contribution to the publications

I T. Arola was the corresponding author, who planned the research, selected the co-authors, performed groundwater energy calculations for the groundwater energy database and wrote approximately 90% of the text.

II T. Arola was the corresponding author, who planned the research, conducted approximately 90% of the fieldwork, performed the data analysis, excluding statistical analysis, and wrote approximately 95% of the text.

III T. Arola was the corresponding author, who planned the research, selected the co-authors, performed the energy demand and groundwater flow calculations and wrote approximately 70% of the text.

Abbreviations

ATES	aquifer thermal energy storage
COP	coefficient of performance
ELY	The Centre for Economic Development, Transport and Environment
GEU	groundwater energy utilisation
GWHP	groundwater heat pump
LNAP	light non-aqueous phase liquids
RES	renewable energy sources
SSPF	seasonal system performance factor
UHI	urban heat island

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1 Introduction

1.1 Background and research environment

Concerns over climate change and the adequacy of conventional energy reservoirs have significantly increased during recent decades. This has forced scientists to develop alternative energy utilisation techniques to compensate for conventional energy use. The use of renewable energy sources (RES) reduces the emissions of greenhouse and air pollution gases, and is not dependent on international energy transport. Hence, the use of RES can be seen as both an environmentally attractive and a local energy option. Several countries around the globe have promoted the use of renewable energy by different methods (Haehnlein et al., 2010). The EU has a commitment to reduce greenhouse gas emissions from 85% to 90% below 1990 levels by 2050 (European Commission, 2011). EU legislation endorses the utilisation of RES and more efficient energy production, mainly through directives 2009/28/EU and 2012/27/EU, which are known as the energy and energy efficiency directives.

Finland is one of the world's leading nations in the utilisation of RES, and the objective of the National Energy and Climate Strategy is to increase the share of renewable energy sources in total energy consumption (Ministry of Employment and the Economy, 2008). In 2012, RES accounted for 35.1% of the overall energy consumption of Finland (Statistics Finland, 2013). By 2020, Finland's share of gross final energy consumption supplied by RES has been targeted at 38% according to EU directive 2009/28/EU.

One option to increase the use of RES is to exploit heating or cooling power from the ground. Energy utilisation from the ground can be divided into two different scientific environments: geothermal and thermogeological (Banks, 2012). Geothermal energy is mainly derived from the earth's interior heat and hence can be exploited at depths of over 400 m from the earth's crust (Haehnlein et al., 2010). The resource for thermogeological energy is mainly solar energy, which is absorbed by and stored in first 400 m of the ground surface (Banks, 2012; Fetter, 1994; Haehnlein et al., 2010).

The energy demand defines the groundwater flux needed to supply the heating and/or cooling energy of the building. Groundwater can form a thermogeological environment for both the heating and cooling of buildings. Groundwater has been widely used for decades as an energy resource, for instance in China (Banks, 2009), North America (Ferguson and Woodbury, 2005) and in Europe (Banks, 2012). The Netherlands is one of the leading groundwater energy users in the world, having over 2740 systems that utilise both heating and cooling energy from groundwater (Sommer, 2014). The estimated amount of circulated groundwater in these systems in 2012 was 248 million m^3 (Sommer, 2014), and energy utilisation may account for the largest usage of groundwater in the Netherlands by the year 2020 (Bonte, 2015). The largest groundwater energy utilisation (GEU) site in Nordic countries is Arlanda airport in Sweden, which operates with a maximum groundwater circulation of 720 m^3/h (Cabeza, 2015). A demonstration heating plant that demanded a maximum of 72 m^3/h groundwater was constructed and operated in Forssa, southern Finland, from 1984–1985 (Iihola et al., 1988). The plant has not been in operation since the demonstration period ended. No large building complexes are heated and/or cooled by groundwater, and hence GEU is still a new RES innovation in Finland. The energy consumption of Finnish buildings has recently been well modelled and established (Kalamees et al., 2012). The Finnish environment, where mean annual air temperature varies between +6…-3 °C (Pirinen et al., 2010), demands significantly more heating than cooling energy in buildings (Jylhä et al., 2011; Kalamees et al., 2012), although some special constructions, such as large data rooms, have significant cooling demands.

Studies on groundwater energy potential have mostly concentrated on two specific issues: 1) the effects of urbanisation on groundwater utilisation and 2) energy storage in aquifers. For example, Allen et al. (2003), Kerl et al. (2012) and Zhu et al. (2010) demonstrated that groundwater under cities can form a significant energy resource. Several studies (e.g. Allen et al., 2011; Benz et al., 2015) have modelled the anthropogenic heat flux in the subsurface, which is the reason for the increased groundwater heating potential in urbanised areas. Aquifer utilisation as an energy store was actively studied in the 1990s, when Andersson (1994) reported that Sweden had several aquifers under investigation for storing energy. Recently, Reveillere et al. (2013) demonstrated that utilising an aquifer for energy storage could provide heating energy to 7500 housing equivalents in the Paris basin area, France.

Previous studies have focused on regions with naturally mild groundwater temperatures from 8 to 15 °C. Hence, the groundwater energy potential in environments with naturally low groundwater temperatures has remained undetermined. Neither has the latest information on the energy demands of buildings been incorporated in groundwater energy system design in the Nordic environment.

1.2 GEU technique

The typical technique for GEU is called an open-loop energy system or open-loop system (Bonte et al., 2011; Haehnlein et al., 2010). This technique extracts thermal energy by pumping groundwater from and discharging it into aquifers. Groundwater is pumped from an abstraction well, transmitted through an energy-transfer system and finally returned to the subsurface via an injection well (Fig. 1). Figure 1 presents a well-doublet scheme (Banks, 2009; Ferguson and Woodbury, 2005) in which one abstraction and one injection well have been constructed. In heating applications, heat is abstracted from groundwater and hence it is returned to the aquifer at a lower temperature than when pumped. If a heat pump is used to produce heating power for buildings, the term groundwater heat pump (GWHP) system is also used. Respectively, in cooling applications, groundwater is injected to the aquifer at a higher temperature than when abstracted.

Energy storage in an aquifer can be combined with GEU systems. In this case, the GEU system is designed to work in two directions, whereby an abstraction well in the summer becomes an injection well in the winter. This means that cold groundwater pumped from an abstraction well in the summer is used for cooling and hence returned to the injection well at a higher temperature. In the winter, the system is reversed and warmer groundwater is utilised for heating purposes. This system is known as aquifer thermal energy storage (ATES) (Andersson, 1998; Bonte et al., 2011).

To work suitably, a GEU system requires a relatively high hydraulic conductivity of soil or rock, from 10^{-5} to 10^{-1} m/s, and a suitable chemical composition of groundwater (Sanner, 2001). A high hydraulic conductivity enables effective groundwater flow while chemical properties of the groundwater, i.e. a high concentration of iron (Fe) and manganese (Mn), together with oxidation during groundwater circulation, may cause the clogging of pipes

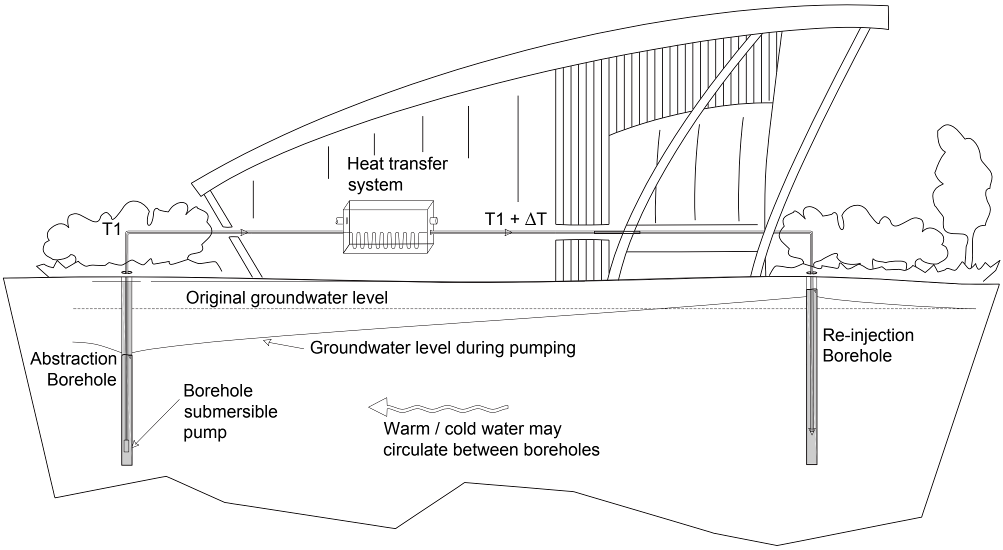

Figure 1. Schematic illustration of an open-loop GEU system. Groundwater at a certain temperature T1 is pumped from an abstraction well or borehole, then led to a heat transfer unit to extract the energy, and finally re-injected back into the aquifer via an injection well. An equivalent amount of groundwater is re-injected into the aquifer to that pumped out of it; only the groundwater temperature changes by the factor ΔT (Figure: courtesy of Golder Associates (UK) Ltd.). Reprinted with permission from Springer (I).

and/or the heat transfer system (Sanner, 2001). Depending on the soil properties, i.e. buffering capacity, a high concentration of carbon dioxide (CO_2) causes acidity and hence elements from minerals may dissolve in groundwater (Trautz et al., 2013), which can cause clogging of pipes and/or the heat transfer system. Chloride (Cl^-) is the main element causing corrosion of GEU systems (Sanner, 2001). An inadequate design or unfavourable environmental conditions may allow excessive groundwater flow from the injection well to the abstraction well, and hence may reduce the efficiency of the GEU system. The low temperature of groundwater will also reduce the system efficiency.

1.3 Heat transport in a GEU system

In areas where the groundwater vertical recharge rate is significantly lower than the groundwater horizontal flow rate, the heat movement in aquifers is mainly dependent on the groundwater flow velocity (Zhu et al., 2014). Due to groundwater flow conditions, horizontal advection is normally the dominant heat transport process in urbanised glaciofluvial sand / gravel aquifers. However, the retardation of heat in aquifers causes the heat frontier to move slower than the groundwater flow. The retardation in groundwater flow is caused by heat transfer between groundwater and soil particles (Bons et al., 2013). Similarly to retardation, non-linear groundwater movement causes the dispersion of heat in porous media (Bons et al., 2013; Molina-Giraldo et al., 2011), which means that heterogeneity within aquifers also affects the advection in GEU systems. If several GEU systems or wells are situated too closely, heat dispersion will cause negative consequences for the thermal balance of the groundwater, and energy utilisation will consequently not remain at a thermally sustainable level (Bakr et al., 2013; Ferguson and Woodbury, 2005).

Heat from solar radiation absorbed by the earth's surface is vertically transmitted deeper into the soil by conduction. The anthropogenic heat flux from, for example, basements, district heating pipes and asphalt is also transferred to soil by conductive heat transport processes. Fourier's law can determine the conductive heat flow, Q_{cond} (W):

$$Q_{cond} = -\lambda A \frac{dT}{dx} \qquad (1)$$

where, λ is material's thermal conductivity (W/m K), A is the cross-sectional area of the material under consideration (m^2) and dT/dx is difference in temperature divided by the distance between two measuring points (K/m), also known as the thermal gradient. Equation 1 describes the amount of heat passing through per unit area.

Based on the Fourier's work, Carslaw and Jaeger (1959) and Domenico and Schwartz (1990) presented the following equation to describe the 2D, x-y plane, transient subsurface heat transport for homogeneous media:

$$\kappa \frac{\partial^2 T}{\partial z^2} = \frac{\partial T}{\partial t} \qquad (2)$$

where κ is the bulk thermal diffusivity (m^2/s) of the subsurface, T is temperature (K), z is depth (m) and t is time (s). Equation 2 can be used to describe the temperature change at any point in a homogeneous medium.

When groundwater is abstracted from an aquifer to an energy transfer system, energy is transferred horizontally by forced convection, i.e. advection. In GEU, heat transfer can be approximated by Isaac Newton's equation (Banks, 2012):

$$Q_{conv} = CHT(T_{solid} - T_{fluid}) \qquad (3)$$

where Q_{conv} (W/m^2) is heat transfer from the solid to the fluid per unit surface area, CHT (W/m^2K) is a coefficient of heat transfer depending on the fluid rate and the fluid and solid material properties, and T_{solid} and T_{fluid} (K) are the temperature of the solid material and fluid, respectively.

Adding a convection term to equation (2), it is possible to simultaneously describe conduction and convection, i.e. longitudinal and transverse heat movement in an aquifer:

$$\kappa \frac{\partial^2 T}{\partial z^2} - (q \frac{C_w}{C_s}) \frac{\partial T}{\partial z} = \frac{\partial T}{\partial t} \qquad (4)$$

where q is fluid velocity (m/s), C_w is the volumetric heat capacity of water (J/m^3K) and C_s is the volumetric heat capacity of the saturated soil matrix (J/m^3K).

The power exploitable from flowing groundwater can be calculated by:

$$G = F \Delta T W_{Hcap} \qquad (5)$$

where G is the amount of heat/cold exploitable from flowing groundwater (W), F is the flux of water (kg/s), ΔT is the temperature difference between incoming and outgoing water in the heat transfer system (a temperature drop in heating mode and temperature rise in cooling mode (K)) and W_{hcap} is the specific heat capacity of water (J/kg K).

When energy is transmitted to a building, the efficiency of the system has to be noted. Efficiency is referred as the coefficient of performance (COP), the value of which depends on the power produced and used. Most often, a heat transfer system is powered by electricity, and hence COP can be measured by:

$$COP = \frac{P_{hc}}{E} \qquad (6)$$

where P_{hc} is the derived amount of heating/cooling power (W) and E is the electricity (W) used.

The heating power, or the heat load, that is producible in a building from flowing groundwater by using a heat transfer system can be calculated by adding the system efficiency to equation 5:

$$H = \frac{F\Delta TW_{Hcap}}{1-(\frac{1}{COP})} \qquad (7)$$

Respectively, cooling power, or the cool load, is:

$$C = \frac{F\Delta TW_{Hcap}}{1+(\frac{1}{COP})} \qquad (8)$$

In equation (7), H is heating power (W), and in equation (8), C is cooling power (W).

Furthermore, the groundwater flux unit, kg/s, is changed to l/s and specific heat capacity is presented as J/l K, respectively, as the change has no real effects on the results and l/s is universally used to describe groundwater flow.

Groundwater temperatures to depths of approximately 10–25 m are generally equal to the mean air temperature in moderate and warm climates (Allen et al., 2003; Kasenov, 2001; Menberg et al., 2013). In contrast, in northern areas, the groundwater temperature is 2 to 6 °C higher than the air temperature (Banks et al., 2004; Ferguson and Woodbury, 2004; Rosen et al., 2001). The main reasons for these temperature differences are the winter snow cover and frost formation in the soil. Snow functions as an insulator, preventing the conduction of cold air into the subsurface layers in the winter. In frost formation, latent heat is released into the soil when groundwater freezes (McKenzie et al., 2007; Soveri, 1985; Woo and Marsh, 2005). Frost also reduces the flow of cold meltwater into deeper soil layers in early spring, when the melting of snow occurs (Soveri, 1985).

1.4 Energy simulations for buildings

The National Building Code of Finland, published by the Ministry of the Environment, guides energy-efficient building design. Based on 30 years of data on annual average air temperatures, Finland is divided into four climatic zones to examine the energy consumption of buildings (Kalamees et al., 2012; Ministry of the Environment, 2012). The total power demand and/or energy consumption of buildings also depends, for example, on the thermal properties of the building envelope, domestic hot water consumption and distribution losses from space heating and domestic hot water. This information provides source data for simulating the heating and/or cooling power (W) demand for different building types. The total energy consumption per year (Wh/a) of buildings can be calculated by summing the hourly power simulations over one year.

In practice, the power demands of buildings define the groundwater abstraction needs. Rosen et al. (2001) stated that for a closed loop geoenergy system, i.e. a system where energy is exchanged from the ground to the fluid inside the heat exchanger pipes, economically the most suitable option is to dimension heat pumps to cover 50% to 60% of the peak design power of individual houses. With this dimensioning, approximately 90% of the yearly energy consumption could be achieved by a heat pump in Sweden (Rosen et al., 2001). Holopainen et al. (2010) modelled a closed loop borehole heat exchanger system and made a life-cycle cost-estimation for dimensioning the heat pump to cover 30% to 90% of the peak heating power of apartment buildings in Finland. They reported that the lowest life-cycle cost will be achieved if a heat pump is dimensioned to cover 50% of the peak design power (Holopainen et al., 2010).

1.5 Environmental and legal aspects of GEU systems

GEU has direct impacts on aquifer temperature and hydrology (Bonte et al., 2011). Hydrological impacts are related to changes in the groundwater level and flow and the capture zone of nearby wells. Depending on the size of the GEU system and the hydrological properties of the aquifer, the impact zone can extend over several kilometres (Ferguson, 2006). At the aquifer scale, GEU has no hydrological impacts, because an equal amount of groundwater is re-injected to an aquifer to that which is abstracted.

Changes in groundwater temperature may have chemical and microbiological impacts (Bonte et al., 2011; Brielmann et al., 2009) and direct impacts on neighbouring GEU systems. In low-temperature (T_{max} < 30 °C) GEU systems, the chemical impacts are mostly related to system function and may cause clogging and corrosion. Groundwater temperature changes may alter the microbiological population and/or introduce or mobilise pathogens into the medium (Bonte et al., 2011). In general, warm groundwater provides a more suitable environment for harmful thermophile microbes such as faecal bacteria than cool groundwater (Brielmann et al., 2009). Brielmann et al. (2009) stated that although low temperature GEU can affect the bacteria and fauna of an aquifer, it is unlikely to threaten ecosystem functioning and groundwater protection in uncontaminated shallow aquifers. Iihola et al. (1988) reported similar results from low temperature aquifer energy storage experiments in Finland. Groundwater-dependent ecosystems in the EU are protected by Directive 2006/118/EU.

Some countries have set legislation or official guides for GEU to protect groundwater reservoirs. For example, Austria has a legally binding operational limit not to change the groundwater temperature by more than 6 K, while the respective limit in Switzerland is 3 K and in France 11 K (Haehnlein et al., 2010). GEU is not mentioned in Finnish legislation. However, the use of groundwater is highly controlled and protected by the Water Act and Environment Act and regulation in Finland. For instance, the Environment Act forbids the emission of substances, energy and/or micro-organisms into groundwater that could cause a deterioration in groundwater quality. An environmental permit must be obtained from the Regional State Administrative Agencies to implement a GEU system if the pumped amount of groundwater exceeds 250 m^3/d. Minor regulations related to GEU are also included in the Land Use and Building Act and Real Estate Formation Act in Finland. The Land Use and Building Act provides regulation related to construction licenses and the Real Estate Formation Act to the location of GEU systems.

GEU may also have positive environmental influences. De Keuleneer and Renard (2015) demonstrated that open-loop well doubles can help remediate seawater intrusion into coastal aquifers. Zuurbier et al. (2013) reported that the remediation of light non-aqueous phase liquids (LNAP), including chlorinated solvents, in groundwater can be accelerated by GEU. Replacing oil heating systems with GEU will reduce the risk of oil leaks to the aquifer and emissions of greenhouse gases. Moreover, no heat carrier fluid is circulated in the subsurface, which makes GEU an environmentally more attractive option than other, so-called closed loop, geothermal energy solutions.

1.6 Objectives and scope

This thesis study examined groundwater energy utilisation in a region where the natural groundwater temperature is low and the heating demands of buildings are high. The thesis connects scientific information on hydro- and thermogeology with energy simulations of buildings to produce accurate results on groundwater energy utilisation.

The study addressed three main objectives. The first of these was to investigate the heating potential of groundwater on a general level in Finland (paper I). Paper I describes the nationwide groundwater energy potential in regions that are already in urban or industrial use. The second objective was to examine whether urbanisation has affected groundwater temperatures in different aquifer types and the potential consequences for the peak heating and peak cooling power potential of groundwater (paper II). As GEU is highly dependent on the groundwater temperature, it is necessarily to recognise the influence of urbanisation on this temperature (paper II). The final objective was to examine whether groundwater can retain its heating/cooling potential in long-term energy utilisation in an area where the natural groundwater temperature is low, 4.9 °C. The energy potential calculations in papers I and II are based on modern groundwater temperatures, i.e. the calculations were performed to describe the peak heating (paper I) and peak cooling (papers I and II) power. In paper III, long-term temperature variations in groundwater caused by energy utilisation and their influence on the energy potential are modelled.

Each objective is addressed with a journal article, and hence each article provides one of the three answers. The research scale of the study ranged from the country (paper I) to the city (paper II) and finally to an aquifer and the property level (paper III). This dissertation summary combines data from the articles from the country to the aquifer and property scale to provide accurate information on the utilisation capacity of groundwater energy.

2 Material and methods

2.1 Finnish thermogeological environment

Groundwater reservoirs in Finland are mostly found in Quaternary, glaciofluvial coarse-grained deposits, i.e. eskers or ice-marginal end moraine complexes, the most extensive of which are the Salpausselkä end moraines. Aquifers are normally unconfined, but semi-confined or confined aquifers also exist, mostly in southern parts of Finland. Semi-confined and confined aquifers are due to clay deposits that overlay sand or gravel sediments. Clays are related to glaciolacustrine or glaciomarine stages or the frequent coverage of the surface of the terrain in southern parts of Finland by the Baltic Sea after glaciation. The hydraulic conductivity of Finnish glaciofluvial sand/gravel aquifers is high, usually between 10^{-5} to 10^{-2} m/s (Hänninen et al., 2000; Rantamäki et al., 2009; Salonen et al., 2014; Salonen et al., 2001), which allows a relatively high groundwater abstraction and injection rate.

Finland's mean air temperature was approximately 2.3 ºC during the time period from 1981 to 2010 (Tietäväinen et al., 2010), and average temperatures of groundwater that are not influenced by urbanisation vary from 3.0 °C in northern to 6.6 °C in southern parts of the country (Backman et al., 1999; Mälkki and Soveri, 1986; Oikari, 1981). According to the Finnish Meteorological Institute, the permanent winter snow cover lasts from 85 to 145 days in southern and 190 to over 225 days in northern parts of the country.

In general, groundwater quality is suitable for low-temperature groundwater energy utilisation and storage in Finland, although the chemical composition of groundwater varies between different parts of the country. High Fe and Mn concentrations exist in confined aquifers of coastal areas, where clay deposits overlay sand or gravel units creating unoxic environment (Korkka-Niemi, 2001). Hatva (1989) reported maximum Fe concentrations of 27 to 37.4 mg/l and Mn concentrations of 1.9 to 2.3 mg/l in aquifers where clays overlay coarse-grained soil material. These circumstances may cause technical obstacles to GEU system functioning. Hatva (1989) reported a medium Cl^- concentration in coastal areas of 46 mg/l and a maximum of 350 mg/l. Hence, Cl^- concentrations in Finnish groundwater are low compared to those of saline groundwater areas (i.e. Khaskaa et al., 2013), and will not cause major obstacles to GEU system functioning.

2.2 Study areas

The study presented in the first paper assessed the groundwater energy potential of the categorised aquifers of Finland, and hence the study area was the whole country. The Centres for Economic Development, Transport and Environment (ELY) have categorised aquifers that are suitable for drinking water utilisation. These classified aquifers have legal status and are commonly referred to as groundwater areas. Three aquifers situated under the cities of Turku, Lohja and Lahti were selected for an investigation of the urbanisation effect (paper II). The Karhinkangas aquifer, located in western Finland, near the Gulf of Bothnia, was chosen as the area for basic groundwater data in paper III. The study areas are indicated in Figure 2. The selection criteria of the aquifers included the availability of groundwater temperature data, geological environment, background information on the soil structure and groundwater conditions (paper II and III) and size of the cities, the availability of groundwater monitoring wells in the city centre, as well as in urban and rural areas of the

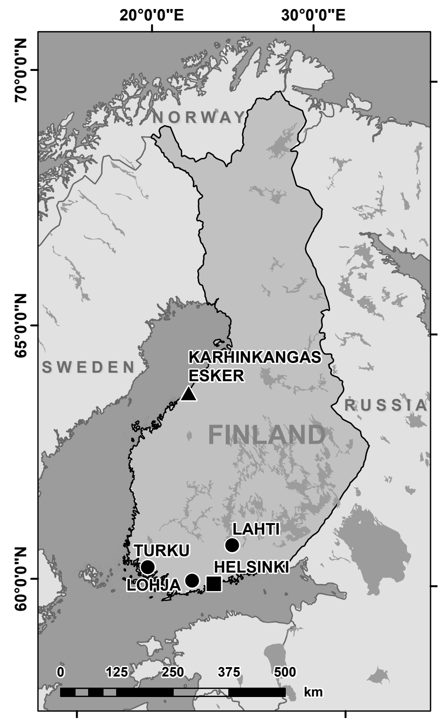

Figure 2. Location map of Finland and the study areas. Finland's capital, Helsinki, is also shown. The sites investigated in paper II are indicated by dots and that in paper III by a triangle (Basemap database © Esri, DeLorme, Navteq. With permission from Golder Associates global ESRI licence).

aquifer (paper II). Aquifers are situated on the glaciofluvial esker (Turku aquifer in paper II and Karhinkangas in paper III) or Salpausselkä I end moraine (Lohja and Lahti aquifers in paper II). Aquifer's hydrogeological features are described more in papers II and III.

2.3 Data collection and processing

2.3.1 Paper I

Each of Finland's aquifers classified for water supply purposes with their land use data was analysed, totalling 5957 groundwater areas. Groundwater data were collected from the Hertta database and land use data from the Corine 2006 database, which are managed by the Finnish Environment Institute. The data from the Hertta and Corine databases were supplemented with personal enquiries and interviews, including one person from each of 15 ELYs during the process. A novel groundwater energy database, combining the aquifer (Hertta database) and land use (Corine 2006 database) information, was created using ArcGis 10 software. To document the exploitable amount of groundwater available for energy production, the groundwater recharge of each aquifer was estimated. Recharge information was collected from the Hertta database. If a particular aquifer had no data in Hertta, the recharge was estimated based on the interviews or on pumping information from water intake plants. Aquifers are often zoned for partly urban or industrial land, and partly outside of these land use forms. The recharge of a portion of an aquifer was estimated by multiplying the recharge of the entire aquifer by the aquifer's proportional land use ratio. The recharge value is used for the value of the groundwater flux in calculations.

The heat power extractable from the groundwater flow, denoted as G (W), was calculated using equation 5. This power describes the potential groundwater heating capacity of Finland. The amount of heat power transportable to buildings using GWHP systems, referred as the heat load H (W), was calculated with equation 7. We used 3K as the value of ΔT, because Finnish groundwater water will not usually freeze, even if 3K is extracted. Based on the studies presented by Allen et al. (2003), Bayer et al. (2011), Saner et al. (2010) and the European Heat Pump Association (EHPA, 2009), a COP of 3.5 was assumed for heating. A COP of 3.5 was expected to describe modern heat pump technology, even in a cold groundwater regime. A COP of 3.5 is also assumed in papers II and III, and hence it is not separately presented in sections 2.3.1 and 2.3.2.

The design power (W/m^2) of detached houses and apartment buildings was simulated with the IDA Indoor Climate and Energy (IDA-ICE) 4.1 dynamic simulation tool. Three different building classes were chosen for simulation: a) house and apartment buildings built before 1960, b) buildings with thermal insulation according to the minimum demands of National Building Code C3, and c) ultra-low-energy buildings. The design power describes the maximum heat demand of a building. The heat demands of buildings in different locations were simulated based on the four climatic zones in Finland (Kalamees et al. 2012). Finally, the surface area of detached houses and apartment buildings that could be heated with power provided by groundwater was estimated. The estimation was completed by dividing the heat load (W) by the design power (W).

2.3.2 Paper II

Groundwater temperatures and piezometric levels were examined in the field from 37 monitoring wells in March 2012 and September 2012. The monitoring wells were chosen to represent rural, urban and city centre areas of cities. The groundwater temperature was measured using a YSI-556 MPS and/or Eijelkamp Diver data logger and the piezometric level using an electronic water level gauge. The groundwater temperature was measured at approximately one-metre intervals from the top of the water column to the bottom of each monitoring well. The weather conditions were also recorded along with land use and possible sources of anthropogenic heat flux to the subsurface near the observation wells.

Statistical analyses were performed using SPSS, STATISTICA and R to describe the dependence of groundwater temperature on land use and to determine the most effective predictors of average groundwater temperatures.

Groundwater temperature data measured in the spring and autumn were combined to calculate the average groundwater temperatures for different land use areas at the aquifer in question. Only temperatures below the zone affected by seasonal temperature fluctuations, i.e. where groundwater temperatures are constant, were used in calculations. The effect of changes in groundwater temperatures on the peak heating power capacity (W) was calculated using equation 7, while the respective effect on the peak cooling power capacity (W) was calculated according to equation 8. It was assumed that groundwater will be cooled to the temperature of 1.0 °C and hence ΔT is 4.5 K if the initial groundwater temperature is 5.5 °C. In cooling calculations, a maximum groundwater return temperature of 12 °C was used in papers II and III. A COP of 25 was used for cooling (Allen et al., 2003) in papers II and III.

2.3.3 Paper III

A reference year of energy consumption by buildings was produced in the first phase. Three types of buildings were simulated: a) 20 detached houses, each with area of 134 m^2, b) three apartment buildings, each with an area of 814 m^2, and c) a 15 000 m^2 shopping centre. The net heating power for a detached house and an apartment building was simulated using the IDA Indoor Climate and Energy (IDA-ICE) 4.1 dynamic simulation tool, and the heating and cooling power demands of a shopping centre were simulated with the RIUSKA application. The simulation results, combined with the power demand of household water heating, the distribution losses from space heating and domestic hot water, were presented as the hourly-based power distribution during a one-year period, named as the reference year. The reference year describes the current Finnish climatic conditions according to Kalamees et al. (2012).

Groundwater flow requirements needed to achieve the reference year's heating and cooling power were calculated on an hourly basis (8760 hours in a year) solving F from equations 7 and 8. The reference year flow demand and an initial groundwater temperature of 4.9 °C were used as a starting point for the groundwater modelling. Groundwater heat transport simulations were based on previous studies on the Karhinkangas aquifer (Paalijärvi and Okkonen, 2014). The groundwater flow model had previously been completed using the three-dimensional finite differences code MODFLOW (McDonald and Harbaugh, 1988). Heat transport was simulated using MT3DMS (Zheng and Wang, 1999) and the analogy between solute and heat transport. A daily time step was used and the total simulation time was 50 years.

Using the modelled changes in groundwater temperatures, it was possible to calculate the variations in energy capacity of groundwater during 50 years of GEU operation. The heating and cooling capacities were calculated according to equations 7 and 8.

3 Results

3.1 Groundwater heating potential in Finland (paper I)

According the novel groundwater energy database, Finland has 801 categorised aquifers for water supply purposes, classified as groundwater areas by the ELYs, under urban and/or industrial land use. The database indicates that 56 464 hectares of Finnish groundwater areas are under urban or industrial land use, and the theoretical replenished groundwater of these exploitable areas is 293 291 m^3/d. According to the results reported in paper I, the exploitable amount of heat power (G) from Finnish aquifers zoned for urban or industrial land use is 42 772 kW. Most of the potentially utilisable groundwater energy areas are located in southern Finland (Fig 3). The Lahti aquifer, with the largest potential, has a theoretical amount of 1960 kW heat. In Figure 3, G values are divided into four power categories: aquifers in the yellow category contain 1 to 100 kW of heating power, light orange 100 to 200 kW, dark orange 200 to 500 kW and red over 500 kW.

If a heat pump with a COP of 3.5 is used, a total of 59 880 kW of heat energy (H) could be distributed to buildings from groundwater. Dividing H by the simulated design power values, it can be estimated that approximately 580 000 m^2 of houses or apartments built before 1960 could be heated with groundwater energy. Respectively, almost 1.3 million m^2 of buildings with thermal insulation according to the minimum demands of National Building Code C3 and almost 1.73 million m^2 of ultra-low-energy buildings could be heated utilising groundwater from classified aquifers that are already in urban or industrial land use.

Assuming that 100% of heating energy is produced by GWHP, 368 aquifers under urban

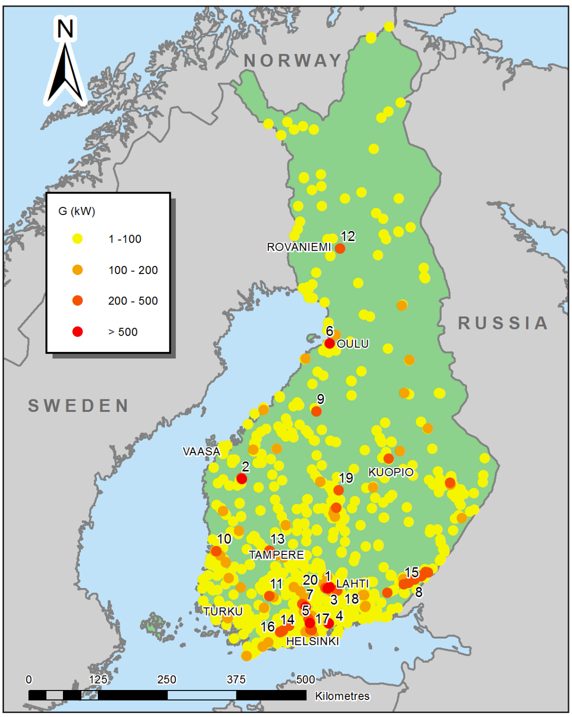

Figure 3. Potential aquifers for GEU in Finland. Each dot represents a single aquifer. The dot colour indicates the categorized amount of heat (G). Numbers from 1 to 20 indicate the location of the 20 aquifers with the largest potential. (Basemap database © Esri, DeLorme, Navteq and Natural Earth). Reprinted with permission from Springer (I).

and/or industrial land use could provide a possibility to heat over 1000 m^2 of ultra-low-energy detached houses. Similarly, 365 aquifers could provide the possibility to heat over 1500 m^2 of ultra-low-energy apartments.

Due to warmer groundwater, the peak heating power was approximately 1.5 times higher in city centres than in rural areas in all the studied cities. Conversely, the peak cooling power was 36 to 50% smaller in city centres than rural areas.

3.2 The effect of the urban heat island (UHI) on groundwater energy utilisation (paper II)

Groundwater temperatures varied between 4.7 and 13.7 °C in the observed monitoring wells. The thickness of groundwater column where the groundwater temperature is affected by seasonal fluctuations varies from 1 to 5 m. The coolest groundwater was observed in rural areas and the warmest in city centres (Fig. 4). Figure 4 presents the results from all temperature measurements in rural, urban and city centre areas in box plot format. These results include measurements from all three aquifers investigated. The median groundwater temperature was 6.2 °C in rural, 7.4 °C in urban and 9.4 °C in city centre areas. According to statistical analyses (ANCOVA), the F-statistic from the variance ratio test between the average groundwater temperature and land use of the areas is 13.7 and $p < 0.005$.

3.3 Long-term groundwater energy potential (paper III)

Due to the high distribution of the energy demand, groundwater flow requirements vary significantly between days, especially in the ATES system. The shopping centre had the largest groundwater circulation demand, as the maximum pumping rate was 121.08 m^3/h, the average being 23.76 m^3/h and the median 18.96 m^3/h. The largest groundwater demand for a day was 1572 m^3, which is 6.5% of the modelled recharge value (Paalijärvi and Okkonen, 2014) of the aquifer. GEU causes at maximum a 15.6 cm change in the groundwater level in the aquifer (heating side of the shopping centre), and abstraction and injection cones occurred at a distance of only a few metres from the abstraction and injection wells.

Thermal plumes occurred when warmer or cooler groundwater was injected into the aquifer. In the scenario for 20 detached houses and three apartment buildings, the groundwater

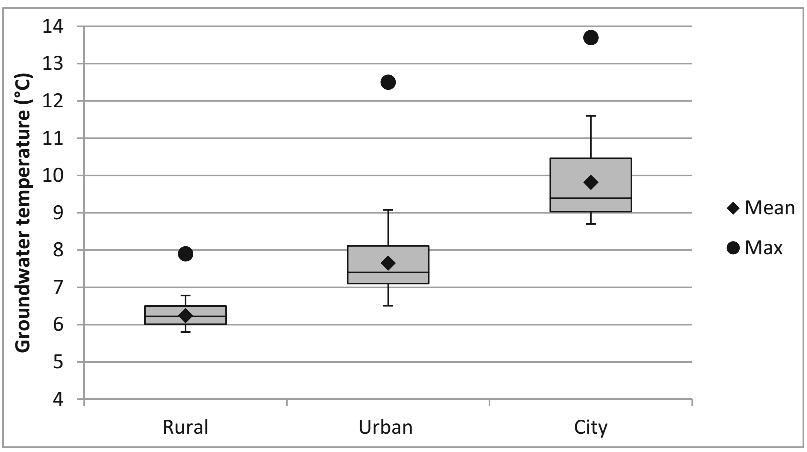

Figure 4. Distribution of the measured groundwater temperatures from all of the studied aquifers. The boxes indicate the 25th and 75th percentiles and the median. Whiskers indicate the 10th percentile (lower) and 90th percentile (upper). The mean and maximum values are also presented. Reprinted with permission from Springer (II).

temperature decreased during energy utilisation, as groundwater was only used for heating (see Fig. 5). The thermal plume extended to 300 m in approximately 30 months after pumping had started and groundwater temperatures achieved a steady state after approximately 2 years of operation. For example, the temperatures remained constant between 2.8 °C and 2.9 °C in the detached house scenario (Fig. 5) and at 3.9 °C in the apartment building scenario at an observation point 300 m from the injection well.

In the shopping centre scenario, in which ATES was modelled, the groundwater thermal plume is more mixed than the well-doubles scheme, because both a warm and cool plume will appear (Fig. 6). Temperature variations in the simulation reached a constant annual cycle after five years of operation on the cooling side and approximately after the first year on the heating side. At the observation point 300 metres downstream from the injection well, the modelled temperature begins to decrease after 27 months of operation. The temperature reaches its minimum level of 2.2 °C after 60 months of operation and then increases to the constant level of 2.3 °C after approximately 100 months of operation (Fig. 6).

In the apartment building and detached house scenarios, energy utilisation had no significant effects on the groundwater temperature in the abstraction well (Fig. 5). The groundwater retained its energy potential during 50 years of GEU operation in our calculations. In the shopping centre scenario, groundwater not only retained but even increased its energy potential due energy storage. January is the peak energy consumption month for heating and August for cooling. In the ATES system of the shopping centre, groundwater would provide over 20% more heating power in January and approximately 190% in July, respectively, when compared to the reference year (Fig. 7). In August, the ATES system would provide over 25% more cooling power compared to the reference year (Fig. 7). Respectively, from January to March and from October to December, the ATES system provides over 50% more cooling.

The groundwater flow was retained at the level of the reference year; only ΔT was changed according the modelled groundwater temperatures in energy calculations in Fig. 7.

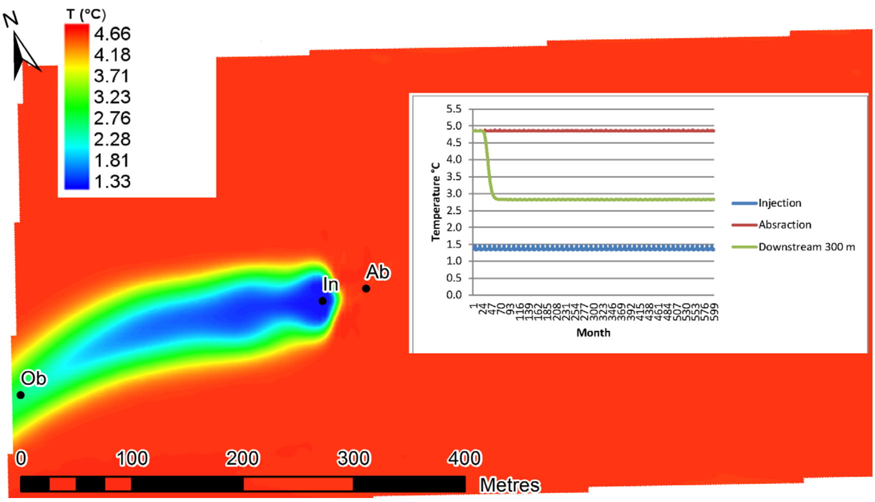

Figure 5. The thermal plume and a diagram showing the modelled groundwater temperatures in the injection (In) and abstraction (Ab) wells and at an observation point (Ob) 300 m from the injection well in the detached house scenario. The plume represents the modelled temperatures after 50 years of operation. The main groundwater flow direction is from east to west.

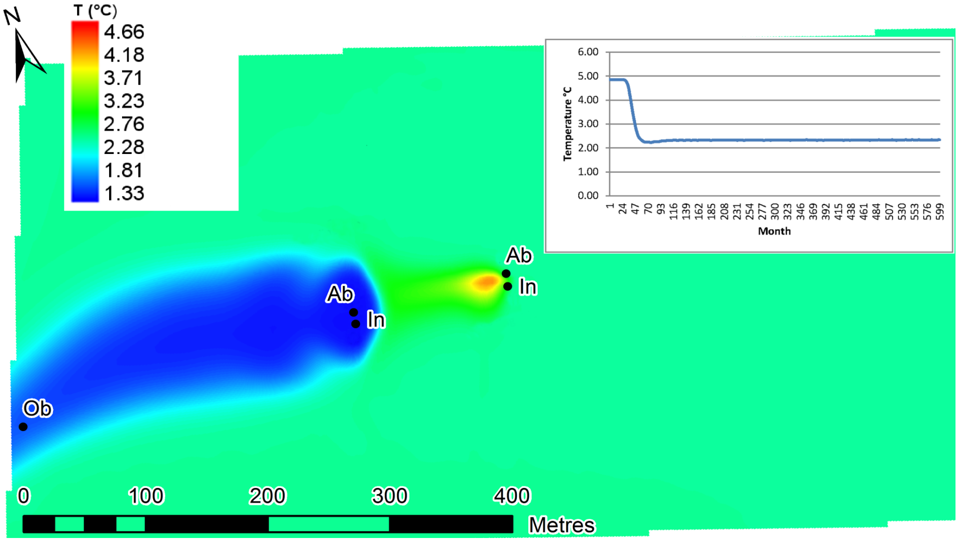

Figure 6. The thermal plume and a diagram showing the modelled groundwater temperature at an observation point (Ob) 300 m from the cooling side in the shopping centre scenario. Ab denotes the abstraction well and In the injection well. The heating side is on the right and the cooling side on the left. The plume represents the modelled temperatures after 50 years of operation. The main groundwater flow direction is from east to west.

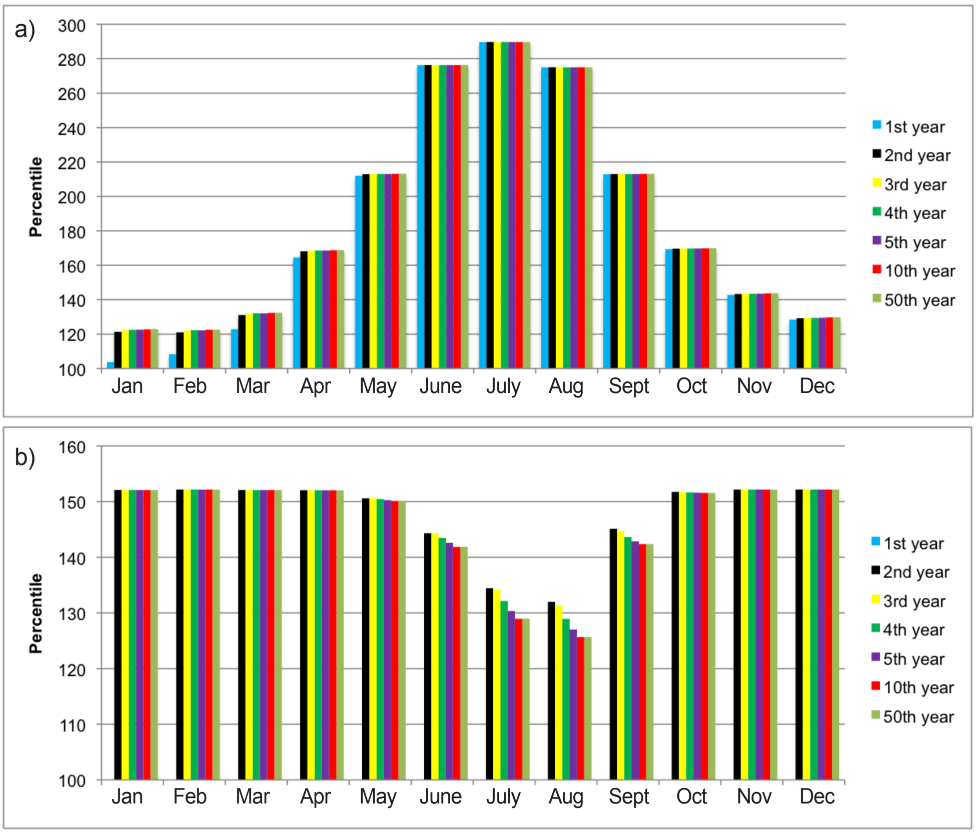

Figure 7. Monthly percentual change in the groundwater energy potential compared to the reference year in the a) heating and b) cooling model for the shopping centre in selected years. 100% indicates the energy demand of the reference year.

4 Discussion

The same methodology was used to calculate the groundwater energy potential at country, city and aquifer scales (paper I to III). The aim was to present a simple method that could be easily implemented in business use to investigate the large- or small-scale geothermal potential of aquifers. The more accurate is the available information on the energy demand of buildings and thermogeology, the more reliable the results will be.

4.1 Hydro- and thermogeological issues

In national energy potential mapping (paper I), it was focused on the Finnish aquifers that are classified as groundwater areas by the ELYs, as official recharge data are only available for classified aquifers. However, the methods used in this study are applicable to all geological or artificial deposits suitable as a source of GEU. The reason for the greater concentration of potential GEU aquifers in the south (Fig. 3) is the higher population density in southern than northern Finland. A higher population density increases the need to recognise groundwater reservoirs, and consequently to classify aquifers for groundwater areas. Areally, the most significant groundwater reservoirs are in the Salpausselkä formations, which are located in Southern and Central Finland (Korkka-Niemi and Salonen, 1996; Mälkki and Salmi, 1970). Hence, geological circumstances also underlie in the southern focus in GEU potential mapping. Aquifers that are not under urban or industrial land use were excluded from this investigation due to the long energy transportation distances, which makes them economically unattractive to utilise at present.

The availability of groundwater and its temperature has the most significant influence on the heating and/or cooling capacity, as can been seen from equations 5, 7 and 8. Well hydraulics will not normally cause problems for GEU in Finland. This is mainly due to the high hydraulic conductivity of Finnish esker aquifers (Hänninen et al. 2000). In northern Finland, the natural temperature of groundwater can be very low, for example 3.0 ºC. Even though groundwater may be easily utilisable in these regions, the relatively low temperature may significantly reduce its heating potential. However, as showed in paper II and recently by Benz et al. (2015) and Menberg et al. (2013), urbanisation has increased groundwater temperatures under cities, and it may therefore be possible to utilise groundwater for heating even in regions where the groundwater is naturally cold. Noting the above and that we used 3K as the value of ΔT, national groundwater energy potential results may be conservative. It is possible that higher ΔT values could be used for many aquifers, especially in southern Finland.

At the city scale, groundwater temperatures increased from rural to urban areas and from urban to city centre areas. The UHI for air temperatures is approximately 1.9 °C in Turku (Suomi and Käyhkö, 2011). Hence, the increased air temperature cannot alone explain the differences in groundwater temperatures. Similar results were reported from Winnipeg, Canada, where an air-related UHI of approximately 1 °C exists, but could not explain the increased groundwater temperatures in urbanised areas (Ferguson and Woodbury, 2004). Anthropogenic heat flow from buildings had the most significant contribution to elevated groundwater temperatures in Turku, Lahti and Lohja. District heating pipes may also have locally elevated the groundwater temperatures, but no clear warming trend near heating pipes was observed. Different forms of urban land use also increased the groundwater temperature. Hence, increased temperatures in urban areas were not only due the groundwater heat transport from the city centre. Suomi and Käyhkö (2011) reported a local UHI effect on air temperatures due to a solitary shopping centre. According our results, similar effects can be seen in groundwater. Even though urbanisation clearly affected the groundwater temperatures, there were significant differences in these temperatures between areas having the same type of land use and aquifer conditions. This may indicate that local, small-scale construction can influence the groundwater temperature. No sites that use groundwater as an energy source are located near our research area. The groundwater flow directions and flow velocity have an important influence on heat plume formation. Hence, it is vital to consider the aquifer structure and hydrogeological aspects together with geochemistry when planning GEU systems.

Statistical analysis confirmed the measured and obtained groundwater temperature results, as a statistically significant correlation was recorded between the groundwater temperature and land use (ANCOVA). The city centre also had the best predication for warm groundwater (RTA). According to RTA, the most effective groundwater temperature predictor is the thickness of the water column in urban or rural land use areas. When the thickness of the groundwater column is less than 8.25 m, the average groundwater temperature is higher than in aquifers with a thicker water column. The results of the statistical analysis can also be explained by heat transport physics. In a city centre, the anthropogenic heat flow to the subsurface arises due to buildings, tarmac, district heating pipes and other heat sources. As the thickness of the water column rises, heat diffuses to a larger area due to horizontal groundwater flow, which reduces the vertical heat movement in the water column. Zhu et al. (2014) reported similar modelled results, according to which an increase in dispersivity decreased the vertical temperature gradient in an aquifer.

In the aquifer-scale investigation, the GEU systems reduced groundwater temperatures and established a cold groundwater plume in the groundwater flow direction. The groundwater temperature decreased by approximately 1 to 2.5 °C from its natural temperature at a distance of 300 m from the site. The relatively high hydraulic conductivity and high water circulation rates allowed the thermal plume to spread over 300 m from the injection well. Similarly, the high hydraulic conductivity and relatively small groundwater circulation demands compared to the estimated natural recharge volume of the aquifer allowed suitable conditions for groundwater abstraction and injection. The hydraulic conductivity of the Karhinkangas aquifer, 1.76 x 10^{-3} m/s, represents that of a typical Finnish sand and gravel aquifer (Hänninen et al., 2000; Rantamäki et al., 2009; Salonen et al., 2014; Salonen et al., 2001). GEU had minor effects on the local hydraulic gradient near the abstraction and injection wells. The ATES system creates different thermal regimes for an aquifer and requires more detailed system planning than groundwater utilisation for heating or cooling only. In a 2D map of the ATES system (Fig. 6), the warm groundwater plume from the heating side collides with the cold plume on the cooling side, and part of the heating plume appears to partially circulate around the cooling plume. The cooling plume in the upstream direction (to the east / southeast in Fig. 6) represents the positive groundwater cone due to groundwater injection into the injection well. A similar upstream plume cannot be seen on the heating side of the ATES system in Figure 6. This is due to the larger heating than cooling demand of the building and hence the larger groundwater injection requirement on the cooling side.

Summer and winter air temperatures fluctuate significantly in the Nordic climate, which causes fluctuations in building energy requirements and hence variations in groundwater circulation demand. Even the ATES system cannot be designed for a relatively stable pumping and injection scenario in the Nordic environment.

4.2 Energy issues

According to the Hertta database, the replenished groundwater from Finnish categorised aquifers is 5.4 million m^3/d. Using 5.4 million m^3/d as the groundwater flux (F) and making a highly theoretical estimation where all that groundwater could be pumped through a heat pump, almost 1200 MW of heat load (H) could be produced by GEU systems. This amount of power could be used to heat over 20 million square metres of housing.

More practical, yet still theoretical, calculations indicate that with the heat load (H) of our database, 60 MW, it would be possible to heat 25 to 40% of annually constructed residential buildings. The residential building construction information is according the official statistics of Finland. In paper I, we assumed that 100% of the heat for buildings would be delivered using a heat pump. As previously shown by Holopainen et al. (2010) and Rosen et al. (2001) in closed loop geoenergy systems, and confirmed by energy demand calculations in paper III for an open loop system, this approach is conservative but indicates the potential to utilise renewable energy.

The only scientifically reported GEU system in Finland, the Vieremä aquifer in the municipality of Forssa, employed a 500 kW heat pump (Iihola et al., 1988). According to the novel national database (paper I), a heat load of 621 kW could be utilised from the Vieremä aquifer. Here, the theoretical heat load calculations in paper I showed a high degree of comparability with practical experience in the Vieremä case.

Groundwater temperature differences between different land use areas were largely similar in all the studied aquifers (paper II). Hence, the ratio of utilisable energy was also similar. Thus, it is possible to estimate changes in the peak heating and peak cooling capacity of an aquifer by measuring the groundwater temperatures and knowing the hydrogeological environment. This estimation can be used as an estimate when mapping the energy potential for large areas. The increased proportional heating capacity in shallow Pleistocene aquifers is rather similar in our investigation to the measurements conducted in Ireland (Allen et al., 2003) and in Germany (Kerl et al., 2012). Allen et al. (2003) calculated that the heating capacity was 1.6 greater in an urban than in a rural area. The groundwater temperature data from Kerl et al. (2012) indicate that that the peak heat power would be at least 1.5 times higher in an urban area than in a rural area. Hence, the urbanisation effect on GEU appears to be proportionally at the same level in areas with mild and low temperature groundwater.

In smaller scale operations, more specific information on the heating and cooling power demands of buildings and hydrogeology is needed. At the property scale, accurate information on the energy demand of buildings provides a possibility for the exact design of GEU systems. Accurate planning allows adjustments in the size of the energy distribution system, e.g. the nominal power of the heat and water pump, which will optimize the building and electricity costs of the project. Careful planning is essential, especially in the Nordic environment, where the operational limits of heat transfer systems are narrow due to the cold groundwater.

In the apartment building and detached house scenarios (paper III), the power requirements for

50 years of operation could be achieved with the groundwater flux demand of the reference year. These results indicate that it is possible to calculate the long-term groundwater energy potential from measured groundwater temperatures before the construction of the system, as the peak heating capacity in paper II equalises the heating energy consumption of the reference year for long-term heating energy utilisation in the Karhinkangas aquifer (paper III). When adding cooling to buildings, i.e. the ATES system in our model, the long-term groundwater energy potential effect could not be estimated without careful groundwater temperature modelling. In the ATES system, the groundwater energy potential increased compared to groundwater utilisation for heating energy only. Approximately 450 MW of heating and 160 MW of cooling power could be distributed to shopping centres for exterior energy use in our model. Naturally, the ATES system would provide more heating in summer and more cooling in winter for exterior use (see Fig. 7). In many cases, such power, especially cooling power in winter, could not be utilised by neighbouring properties. If heating and/or cooling power cannot be distributed for external use, the groundwater abstraction requirements decrease significantly from the pumping demands of the reference year. In the long term, using the ATES system, approximately 60 000 m^3 less groundwater would need to be abstracted to meet the reference year energy requirements of the shopping centre.

The modelled groundwater temperature variations in abstraction and injection wells indicate that groundwater could effectively be utilised until the groundwater temperature reaches approximately 4 °C. Technically even colder groundwater could be utilised, but the groundwater pumping demand would then significantly increase and the effectiveness of the system would decrease.

4.3 Environmental issues

Using groundwater mostly for heating, i.e. injecting cooled groundwater into the aquifer, may provide a solution to reduce the urbanisation impact (paper II), which raises groundwater temperatures. Cool groundwater is also a benefit if groundwater is distributed to the communal water system. However, cooled and/or heated groundwater can change the natural vegetation of groundwater discharges areas and may consequently form a threat to endangered species. Using GEU to replace oil heating systems reduces soil and groundwater contamination risks and hence can improve the environmental conditions of aquifers.

We used moderate ΔT values in the theoretical calculations in papers I and II. The ΔT in paper I was 3 °C and a groundwater temperature of 12 °C was used as the maximum groundwater injection temperature in paper II. The modelled GEU systems (paper III) reduced groundwater temperatures by approximately 1 to 2.5 °C from the natural temperature at a distance of 300 m from the site. The observed temperature variations in paper III are under the temperature limit of 3 °C in Swiss legislation, which is the strictest legally specified numerical temperature fluctuation limit (Haehnlein et al., 2010). Banks (2009) and Ferguson and Woodbury (2005) investigated the cooling effects of buildings on groundwater and reported problems related to an increased groundwater temperature. Comparing their results with ours, it appears that the thermal effect of groundwater energy utilisation is less harmful when more heating than cooling power is needed in buildings.

4.4 Study limitations

The estimation of groundwater recharge is the biggest source of error when theoretical groundwater abstraction in used. The amount of abstracted groundwater has a direct effect on energy utilisation. When the research scale increases, the potential error also increases. In the nationwide research (paper I), recharge values provided by the Hertta database was used as the groundwater flux (F) in our calculations. In the database, recharge values are calculated based on assumptions that precipitation, the hydrological cycle and the porosity of soil are constant over the entire aquifer, which is not the case in most shallow Quaternary aquifers. The variable soil and hydrogeological conditions, for example the thickness and foliation of soil layers, causes differences in groundwater flow velocity, direction and percolation. However, the Hertta database is the only nationwide database that includes groundwater recharge values, and hence it was used in this research. In paper II, the recharge errors of the Hertta database was avoided by using the Water Rights Court permit values for groundwater pumping as F-values.

The effectiveness of a heat transfer system varies over time, especially in the Nordic environment. The higher the difference is between the inlet and outlet temperature of the heat pumps, the lower is the system effectiveness. As the groundwater temperature equalises the inlet temperature of the heat pump, cold groundwater may reduce the COP value. The COP value describes the efficiency of a heat pump in any given time frame. Hence, the COP in winter can vary significantly from that in summer, and the yearly COP value is a rough average of heat pump or heat exchanger capability. The efficiency of a heat transfer system over a year is measured by the system seasonal performance factor (SSPF), which is dependent on variable site characteristics such as the geology, climate and geothermal gradient (Bayer et al., 2011; Banks, 2012). There is no known measured information on the COP from Finnish GEU systems. We preferred COP in our studies, because the calculations were not site- or system-specific (papers I and II), and no measured information on the SSPF was available for paper III.

5 Conclusions

Groundwater forms a significant local renewable energy resource in Finland. The Finnish thermogeological environment, with the effect of urbanisation, is favourable for GEU. As GEU is dependent on the existence of thermogeologically, geographically and geochemically suitable aquifers, which are only located in certain parts of the country, groundwater provides a local energy source.

This investigation demonstrated that approximately 56 500 hectares of Finnish aquifers classified for water supply purposes, comprising 801 groundwater areas, are under urban or industrial land use. The groundwater of these urban and industrial areas contains 40–45 MW of heating power. Assuming a COP of 3.5, 55 to 60 MW of heating power could be utilised from these aquifers using heat pumps. With this amount of power, almost 1.3 million m^2 of standard detached housing and over 1.7 million m^2 of modern ultra-low-energy detached housing could be heated by GWHP systems. This approximation is conservative, as it is assumed that 100% of buildings are heated with GEU and the urbanisation effect has not been considered.

Urbanisation increases the groundwater heating capacity in Finland. The average groundwater temperatures below the seasonal fluctuation zone were 1.3 to 2.0 ºC higher in the urban area and 3.0 to 4.0 ºC higher in the city centre of the investigated cities than in the rural areas around them. Warmer groundwater enables the utilisation of a 50% to 60% higher peak heating load from the city centre than rural areas in Turku, Lohja and Lahti. Respectively, the peak cooling loads are approximately 40% to 50% lower in populated areas compared to rural ones. However, groundwater still constitutes an effective cooling energy utilisation process in Finland, because groundwater temperatures, even in urbanised areas, remain below air temperatures during the summer and the COP for cooling is extremely high. Cooling is also only needed for a limited period in Finland, mostly from June to August. Groundwater energy utilisation may also have environmentally beneficial side effects in urbanised areas, as energy use could reduce the groundwater temperature towards its natural level.

Groundwater energy utilisation reduces groundwater temperatures in the groundwater flow direction. In the Nordic environment, the groundwater temperature decreases due to the significantly larger heating than cooling energy requirements. In glaciofluvial esker formations, the size of the groundwater thermal plume is dependent on site-specific thermo- and hydrogeological factors.

This research demonstrated that careful, interdisciplinary planning involving thermogeologists and HVAC engineers can improve the sustainability and economic viability of geothermal energy utilisation. Accurate planning may reduce the environmental risks, and the overall economics of the energy system could be improved. This research also indicates that the long-term maximum energy potential of groundwater can be estimated when the natural groundwater temperature, geological and hydrogeological conditions of the aquifer and energy requirements of buildings are precisely known.

Further research is recommended to optimize the design of GEU systems. For example, the climate change scenario for the Nordic environment and anthropogenic heat flux estimation related to buildings/land use type could be considered in GEU design for business use. The speed of the urbanisation effect on groundwater and its energy potential is unknown, but could be measured in areas where construction will take place during the coming years.

The same thermogeological methods can be used to evaluate the groundwater energy potential at national or property scales. The results of this thesis represent the Finnish geological environment, but are applicable to all aquifers with suitable groundwater temperature, hydraulic conductivity and transmissivity for thermogeological groundwater utilisation.

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